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OPTIMUM USE OF VISCOUS DAMPERS IN MULTI-STORY STEEL BUILDINGS FOR UPGRADING THEIR SEISMIC BEHAVIOR

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ABSTRACT

This paper discusses the optimum use of viscous dampers along the height of a multi-story steel building in order to minimize its seismic responses, based on the amount of 'received energy'. This is defined as the part of total input energy which refers to the positive work of the base shear force acting on the building foundation during an earthquake. For this purpose at first some typical steel buildings were designed based on the old versions of seismic codes in order to make them similar to the vulnerable existing ones. In the second step, various configurations were considered for dampers, including a) one damper just in one of the stories, creating *n* configurations, *n* being the number of stories in the building, b) *m* dampers (*m*= 2, 3, …, *n*), each in one of the *m* uppermost stories, creating *n-1* configurations, and c) *m* dampers (*m*=2, 3, …, *n*-1), each in one of the lowermost stories, creating *n*-2 configurations. Various damping coefficient values were also considered for damper(s) in each of the above states to find out how this value affects the maximum responses. Besides, in each case, several earthquake accelerograms were used in the time history analyses to realize how the characteristics of earthquake are effective in the response values. Regarding that using dampers in various stories makes the damping matrix of the building non-proportional, a program was developed in MATLAB environment for calculating the seismic response of MDOF systems with nonclassical damping. Numerical results show that for any given earthquake a specific damping value leads to minimum received energy and base shear response almost in all combinations of dampers. Results also show that using two dampers instead of one causes a remarkable response reduction, while adding another damper leads to only a little more response reduction. Based on the results it can be said that by using just a few dampers in some stories it is possible to make the displacement and acceleration responses limited to some desirable level.

Introduction

The use of dampers for reducing the seismic response of structures and optimizing their damping values or their placement in buildings' structures is not a new concept, and the first

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studies in this regard goes back to early 80s (De Silva 1981). Some studies with regard to optimizing the use of dampers in building systems against earthquakes have been undertakedn such as: Optimum design of a first story damping system (Constantinou and Tadjbakhsh 1983), optimal positioning of dampers in multi-body systems (Giirgoze and Muller 1992), optimization methods for passive damper placement and tuning (Milman and Chu 1994), optimum viscous dampers for stiffness design of shear building (Tsuji and Nakamura 1996), optimal damper placement for minimum transfer functions (Takewaki 1997), optimal placement of energy dissipation devices for three-dimensional structures (Wu et al. 1997), optimal use of viscoelastic dampers in building frames for seismic force (Shukla and Datta 1999), optimal placement of passive dampers on buildings using combinatorial optimization (Agrawal and Yang 1999), optimal seismic response control with dampers (Singh and Moreschi 2001), a method for the design of optimal damper configurations in MDOF structures (Garcia 2001), optimal design of passive energy dissipation systems based on h∞ and h2 performances (Yang et al. 2002), a strategy for the optimization of damper configurations based on building performance indices (liu 2002), optimum distribution of viscous fluid dampers in structural systems (Raju et al. 2004), optimal design of viscous dampers for multi-mode vibration control of bridge cables (Wang et al. 2005), and controlling all inter-story displacements in highly nonlinear steel buildings using optimal viscous damping (Attard et al. 2007).

It is seen that in spite of several studies on the optimum use of dampers in seismic response reduction of building systems, no study has been conducted with regard to minimizing the earthquake input energy as a criteria for optimizing the use of dampers. This paper discusses how to decide on the number, the value of damping coefficient, and the location of viscous dampers along the height of a multi-story steel building to reduce the maximum values of each of its seismic responses, particularly story drifts and/or total or absolute accelerations to some desired levels for a given earthquake, or to an acceptable level for a group of earthquakes. The amount of 'received energy' by the building structure during the earthquake has been used as the main optimization criterion for this purpose. Received energy is that part of the total input energy which refers to the positive work done by the base shear force acting on the building foundation during an earthquake, as described hereinafter.

Minimizing the Earthquake Input Energy

The total work which is done by the shear forces, V_b, applied by ground to the building foundation during an earthquake, or the total earthquake input energy, can be stated as:

$$E_{Earthquake} = \int_0^t V_b.\dot{x}_g(t).dt \tag{1}$$

where $\dot{x}_g(t)$ is the ground velocity. This work can be divided into two parts, a positive part and a negative part. The positive part can be considered as the energy which is transferred form ground to the building, and can be called 'the instantaneous accumulated received energy', or simply 'received energy' while the negative part can be considered as the energy which is returned back from the building to the ground, and can be called 'the instantaneous accumulated returned energy' or simply 'returned energy'. Obviously, if the positive work or received energy can be reduced in some way, it will be helpful for the building safety. One way for this purpose is to use dampers, which can be optimized by minimizing the amount of received energy, as described in the following section.

Optimum Use of Dampers

To find out whether the optimum use of dampers is possible, at first some typical steel buildings, with 4, 6, and 11 stories were designed based on the old versions of seismic codes to make them similar to the vulnerable existing ones. Table 1 shows the stiffness coefficients and masses of these buildings.

Table 1. Values of stiffness coefficient and mass of the studied buildings

No. of Building's Stories	Story No.	K_X (kN/m)	K_Y (kN/m)	Story Mass (ton)
4-story	1	51492	43484	55.3
	2	28019	21991	55.3
	3	23166	19455	55.3
	4	21917	17276	55.3
6-story	1	54289	54319	67.76
	2	30409	30194	667.7
	3	29909	29602	67.76
	4	29144	28870	67.76
	5	17204	17147	67.76
	6	16239	16210	67.76
11-story	1	819754	779128	291
	2	423575	396076	291
	3	392730	266056	291
	4	298703	281194	291
	5	275709	258056	291
	6	273701	256524	291
	7	265365	247746	291
	8	188512	178390	291
	9	144441	122783	291
	10	88308	84500	291
	11	59954	63935	291

In the second step, various configurations of viscous dampers all with the same damping coefficient were used for upgrading the building's seismic behavior. These configurations include: a) one damper just in one of the building's stories, creating *n* configurations, *n* being the number of stories of the building, b) *m* dampers (*m*= 2, 3, …, *n*), each in one of the *m* uppermost stories, creating *n*-1 configurations, denoted in the next section by, respectively, 1t, 2t, 3t, etc., of which one is the configuration with dampers in all stories, and c) *m* dampers (*m*=2, 3, …, *n*-1), each in one of the lowermost stories, denoted in the next section by, respectively, lb, 2b, 3b, etc., creating *n*-2 configurations. These are in total 3*n*-3 configurations for an *n*-story building. Various damping coefficient values were considered in each configuration to find out how this value affects the maximum responses. In each case, accelerograms of Kobe (TAK00 component), Northridge (ORR090 component), and Tabas (DAY-TR component) earthquakes, respectively corresponding to low, mid, and high frequency excitations, were used for Time History Analyses (THA), to realize how the specifications of earthquake are effective in the response values. It is worth mentioning that the damping matrices of buildings with dampers in some of their stories are of nonclassical type, for which the conventional modal response combination approach can not be used. Therefore, the response time histories were obtained by using a program, developed in MATLAB environment for calculating the seismic response of MDOF systems with nonclassical damping.

Numerical Results

Numerical results, obtained by almost 2000 cases of THA, include the maximum absolute acceleration, maximum relative velocity and drift, and maximum elastic and damping force of all buildings in all of their stories, as well as the maximum received energy by the building and its maximum shear force in each of the aforementioned combination of dampers. Only few samples of numerical results are presented here due to the lack of space. More results can be found in the main report of the study (Malek 2009). Fig. 1 shows a set of numerical results, related to the last story of the 6-story building.

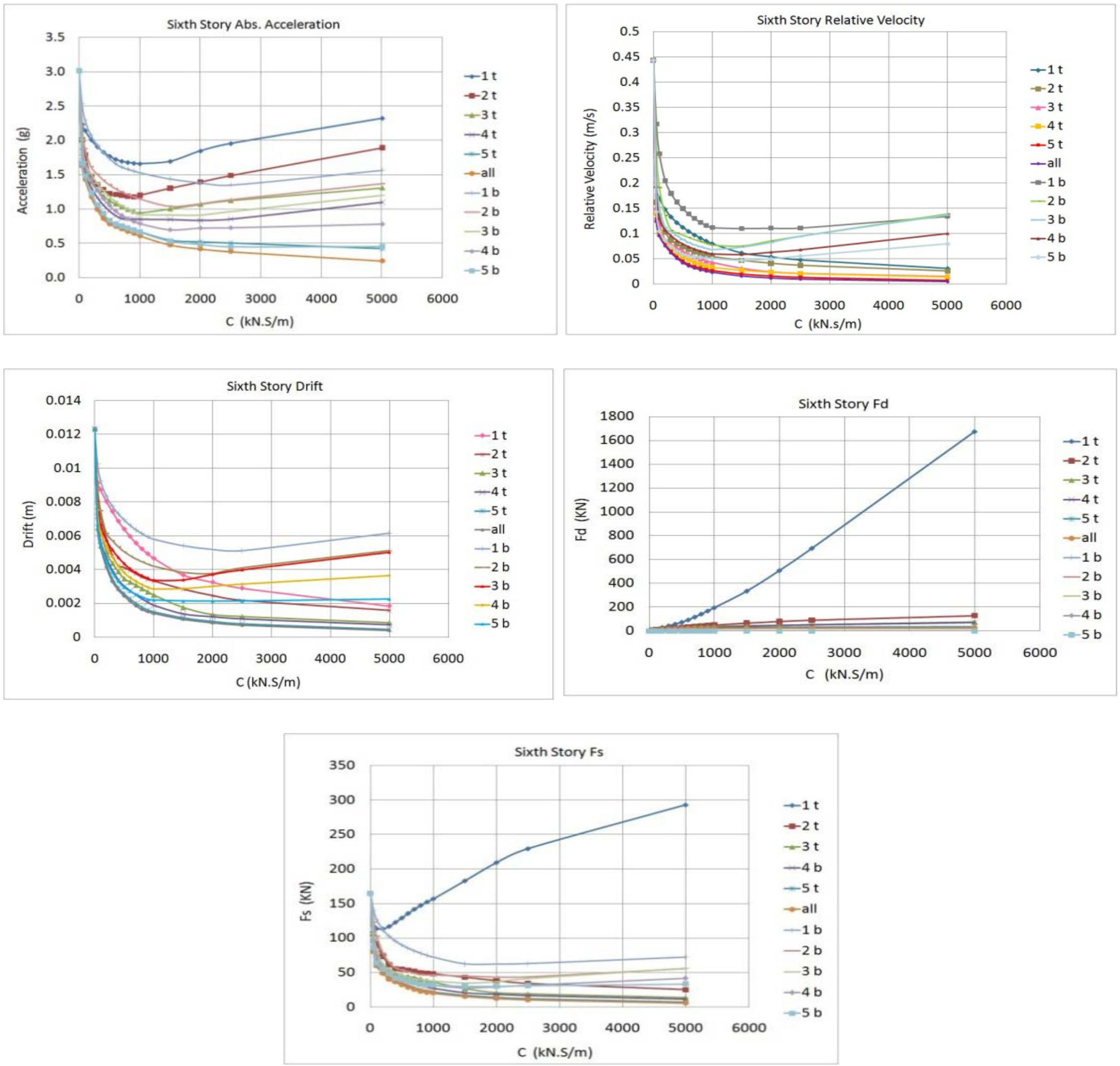
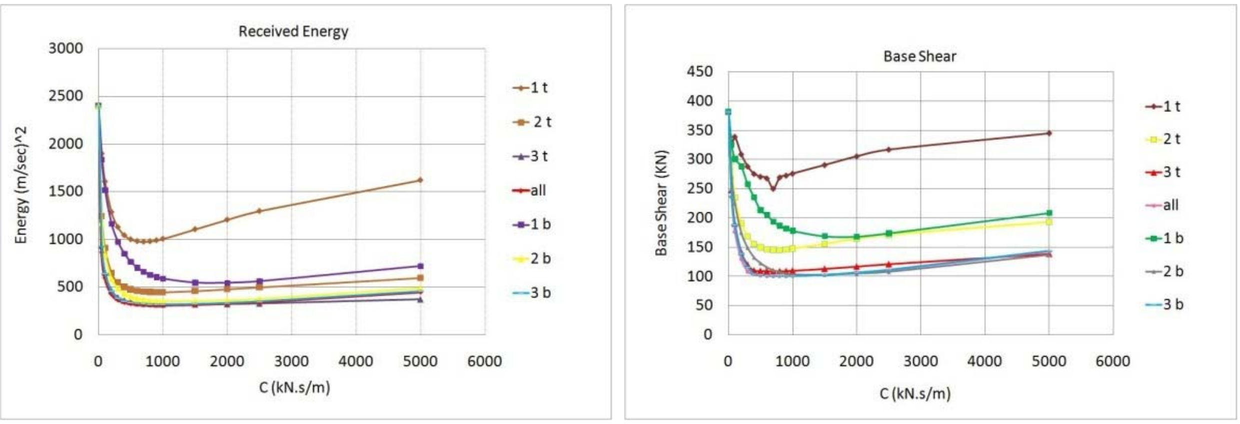
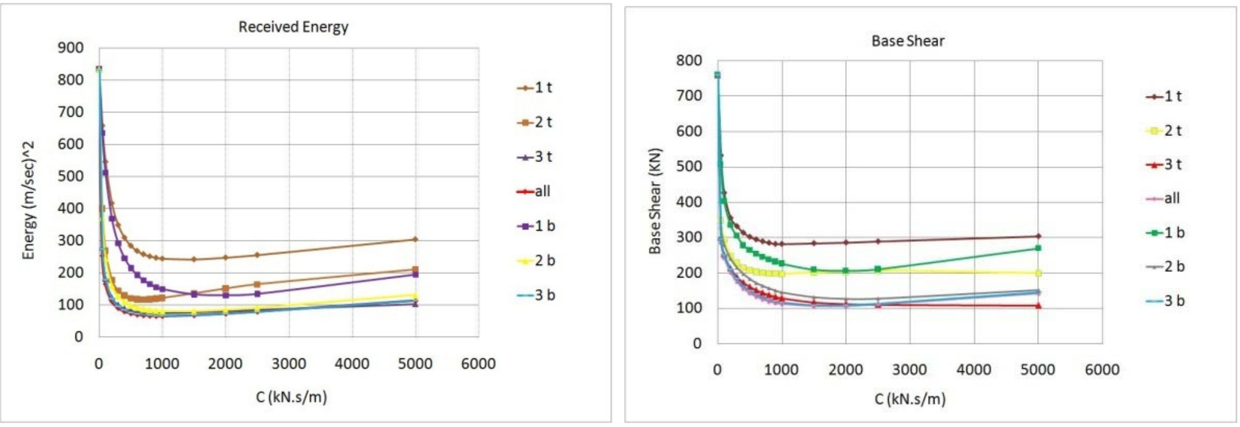


Figure 1. Maximum absolute acceleration, maximum relative velocity and drift, and maximum damping and elastic forces of the last story of the 6-story building subjected to Northridge earthquake (notations 1t, 2t, 3t, etc. and also 1b, 2b, 3b, etc. have been introduced in the previous section of the paper.)

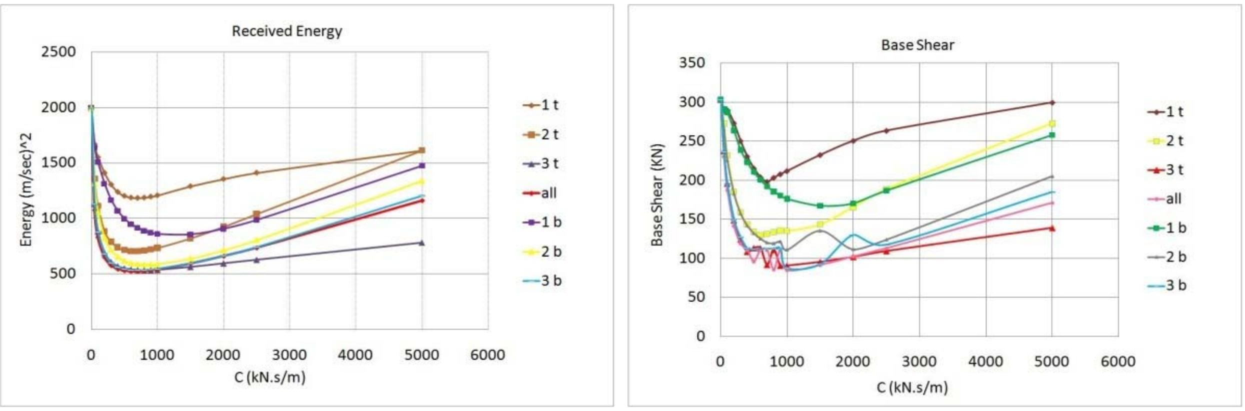
It is seen in Fig.1 that using a damping coefficient value of 1000 kN.s/m results in a relative minimum in most of the response curves. It is also seen that using two dampers each in one of the 2 top stories causes remarkable decrease in response values comparing to the case of using dampers only in one top story, but installing dampers in more stories does not have that much effect. This is while most of the current codes/guidelines suggest using dampers distributed over all levels.



a) Subjected to Kobe earthquake



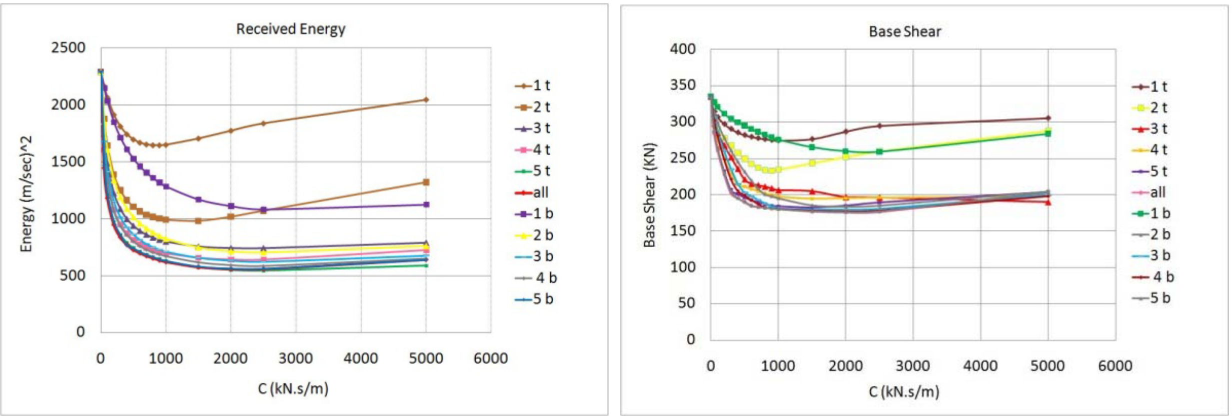
b) Subjected to Northridge earthquake



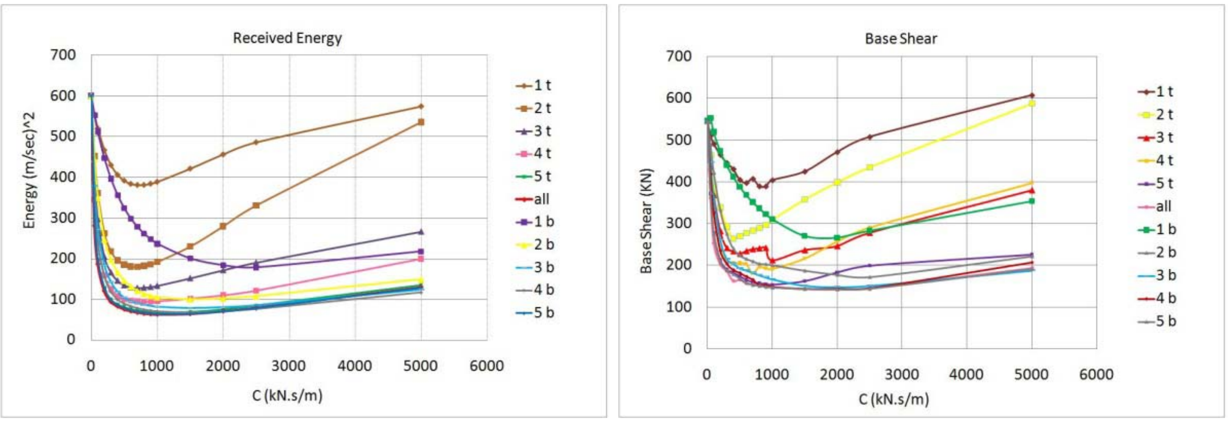
c) Subjected to Tabas earthquake

Figure 2. The maximum received energy and maximum base shear force of the 4-story building in cases of using various configurations of dampers

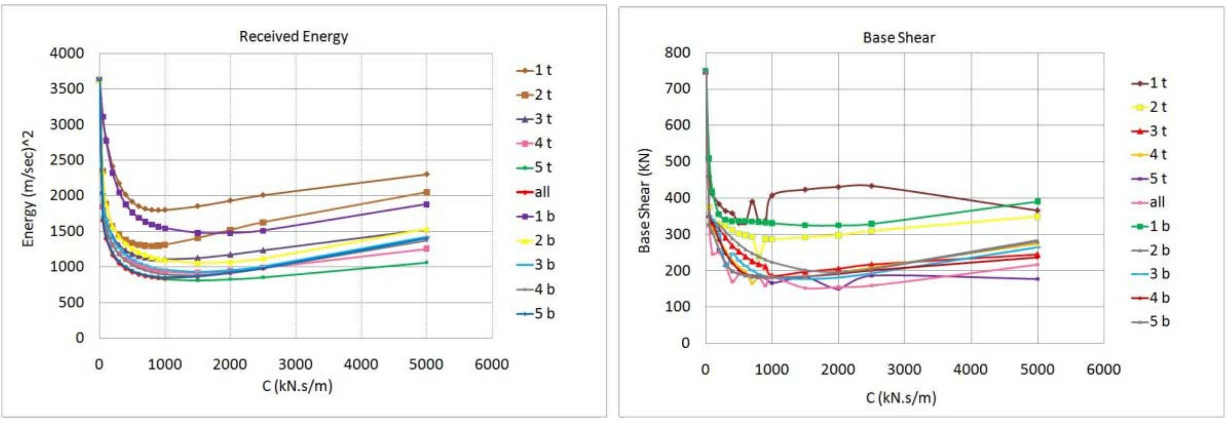
Figs. 2 to 4 show the maximum received energy and the maximum base shear force of the 4-, 6-, and 11-story buildings, respectively, subjected to Kobe, Northridge, and Tabas earthquakes, in cases of using various configuration of dampers in their upper or lower stories.



a) Subjected to Kobe earthquake

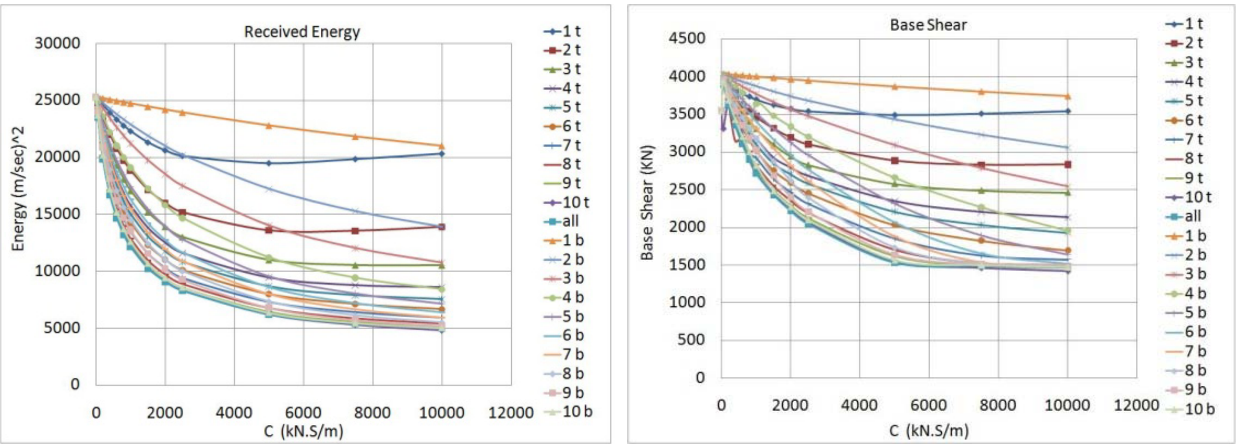


b) Subjected to Northridge earthquake

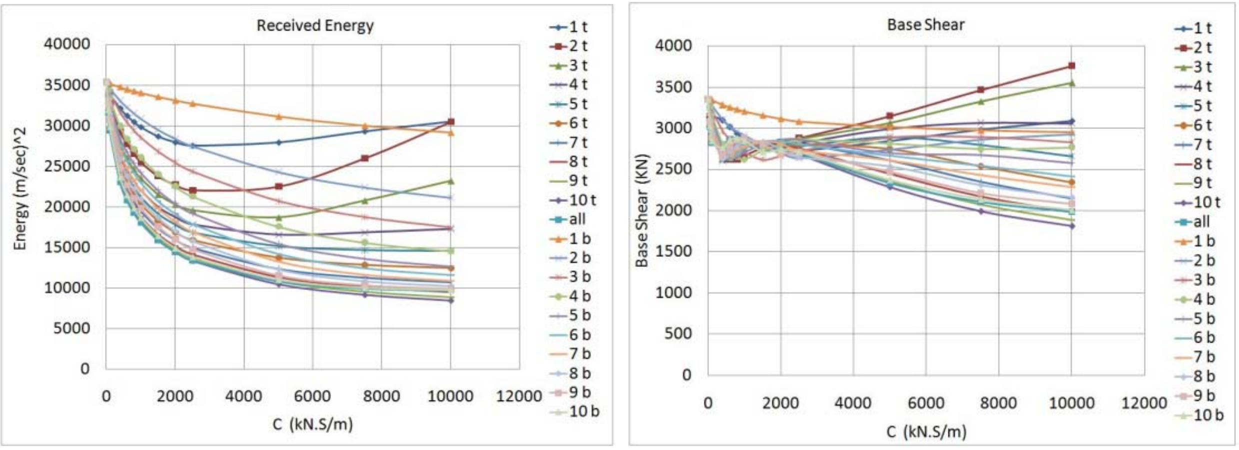


c) Subjected to Tabas earthquake

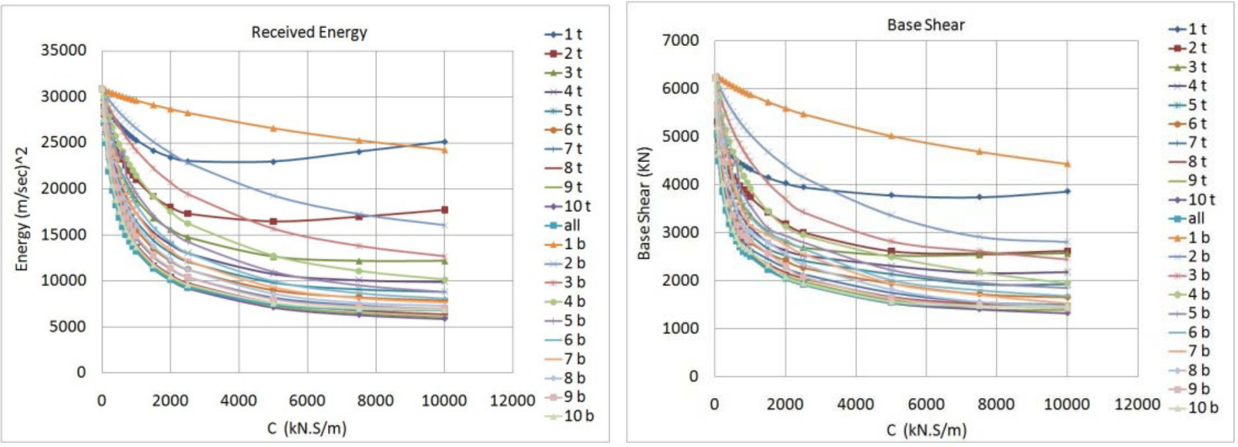
Figure 3. The maximum received energy and maximum base shear force of the 6-story building in cases of using various configurations of dampers



a) Subjected to Kobe earthquake



b) Subjected to Northridge earthquake



c) Subjected to Tabas earthquake

Figure 4. The maximum received energy and maximum base shear force of the 11-story building in cases of using various configurations of dampers

Looking at Figs 2 to 4 one can realize that using dampers in the two uppermost stories of buildings in all cases, seems to be an optimal option for achieving a relatively remarkable response reduction, from both received energy and base shear point of view. It can also be seen in Figs 2 to 4 that the amount of optimum damping coefficient slightly increase with increase in the number of building stories, however this value is almost independent of the earthquake frequency content.

Effect of Dampers in the Axial Forces of Columns

It is obvious that installing a damper as a diagonal member in any bay of a frame causes additional axial forces in the columns of that bay during an earthquake. To find out about this additional axial force, a single story portal frame with a diagonal viscous damper was considered as shown in Fig. 5.

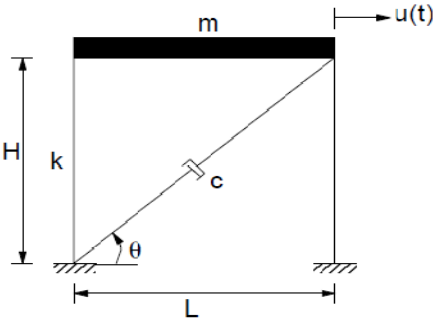


Figure 5. Single story portal frame with inclined viscous damper

The portal frame, shown in Fig. 5, was analyzed subjected to El Centro earthquake, using OPENSEES software, in two states of horizontal and diagonal dampers. The maximum values of column's axial force were obtained in the two states and their ratios were calculated for different values of natural period, T_n, and damping ratio, ζ, of the system. Fig. 6 shows the variation of this ratio with different values of system dynamic properties.

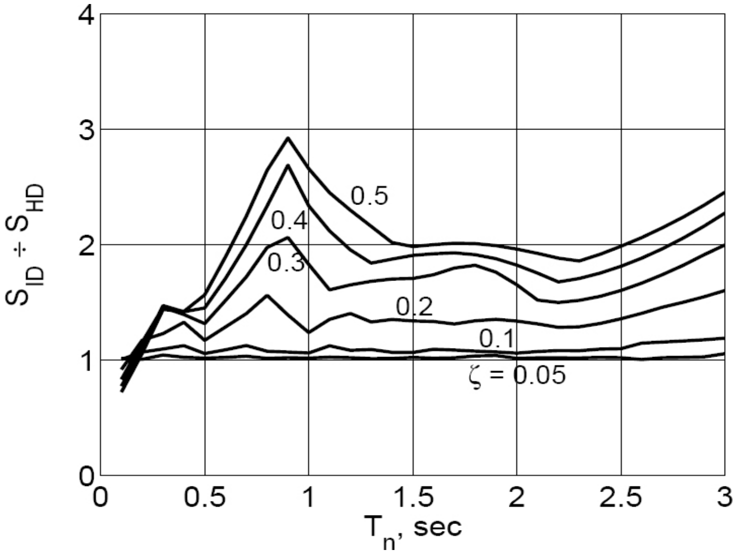


Figure 6. Variation of the ratio of 1-story frame's column axial forces in two states of inclined and horizontal dampers with different values of the system dynamic properties

It is seen in Fig. 6 that the ratio of column's axial force value in case of inclined damper, S_{ID}, to this value in case of horizontal damper, S_{HD}, has a maximum value of about 3 for damping ratio of 0.5 and $T_n = 0.8$ sec. This is while for damping ratios lower than 0.2 this value is almost constant in the whole range of T_n. However, it should be noted that these results may not be the same in general. On this basis, it can be recommended that in order to make sure that the additional axial forces in columns, due to diagonal dampers, does not lead to the failure of columns, either the dampers need to be installed horizontally, or if they are diagonal, they should be installed in more than two bays of the frames.

Conclusions

Based on the seismic response analyses of 4-, 6-, and 11-story buildings in this study and the obtained numerical results, it can be said that:

- Using dampers in a structure does not necessarily leads to the reduction of its seismic response. Particularly with regard to the seismic received energy, adding the value of damping in the building structure to some level, results in the decrease of the received energy, but with more increase in damping values the amount of this energy increases again.
- Some fluctuations in the base shear values is observed with varying the damping values, which can be related to closeness of the fundamental damped period of the system with some specific amount of damping to the dominant frequency of the seismic excitation. However, these fluctuations are not observed in the values of received energy.
- For any given earthquake a specific damping value leads to minimum response almost in all combinations of dampers in various stories. Furthermore, the optimum placement of dampers is almost independent of the frequency content of the applied earthquake.
- As expected, using more dampers results in more reduction of response values, however, this response reduction does not vary linearly with number of dampers. In fact, using two dampers, instead of one, causes a remarkable response reduction, while adding another damper leads to only a little more response reduction.
- By using just a few dampers in some stories (mainly two upper stories) it is possible to make the displacement and acceleration responses limited to some desirable level. This means that the optimum use of dampers for seismic retrofit is possible in most cases in an economical manner.
- Finally, regarding the effect of dampers in the axial forces of columns, horizontal orientation of dampers much better than the inclined orientation.

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